

Delange's Tauberian theorem and asymptotic normality of random ordered factorizations of integers

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Abstract

By a suitable shifting-the-mean parametrization at the Dirichlet series level and Delange's Tauberian theorems, we show that the number of factors in random ordered factorizations of integers is asymptotically normally distributed.

1 Introduction

Let \mathcal{P} be a fixed subset of $\{2, 3, \dots\}$. Let $a(n)$ denote the number of different ways of writing n as the product of *ordered* sequences (n_1, \dots, n_k) of integers in \mathcal{P} . Define $a(1) = 1$. Let $A(N) := \sum_{1 \leq n \leq N} a(n)$. Assume that all $A(N)$ factorizations of an integer $\leq N$ are equally likely; denote by Y_N the random variable counting the number of factors in a random factorization. We prove in this paper that the distribution of Y_N is asymptotically normal under very general conditions on \mathcal{P} .

Denote by $\mathcal{P}(s)$ the Dirichlet series of \mathcal{P}

$$\mathcal{P}(s) := \sum_{n \in \mathcal{P}} n^{-s}.$$

Assume the abscissa of convergence of $\mathcal{P}(s)$ is κ . Then $\kappa = -\infty$ if $|\mathcal{P}| < \infty$ and $0 \leq \kappa \leq 1$ if $|\mathcal{P}| = \infty$. Note that $\mathcal{P}(\kappa) \leq \infty$.

Our main result is as follows.

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Theorem 1. Assume $|\mathcal{P}| \geq 2$ and $1 < \mathcal{P}(\kappa) \leq \infty$; thus there exists $\rho > \max\{\kappa, 0\}$ such that $\mathcal{P}(\rho) = 1$. Let

$$\mu := -\frac{1}{\mathcal{P}'(\rho)}, \quad \text{and} \quad \sigma^2 := \mu^3 \mathcal{P}''(\rho) - \mu.$$

Then

$$\frac{Y_N - \mu \log N}{\sigma \sqrt{\log N}} \xrightarrow{d} \mathcal{N}(0, 1),$$

where \xrightarrow{d} stands for convergence in distribution and $\mathcal{N}(0, 1)$ denotes the standard normal distribution. The mean and variance of Y_N are asymptotic to $\mu \log N$ and $\sigma^2 \log N$, respectively.

By Cauchy-Schwarz inequality, $\sigma^2 > 0$. We will indeed prove convergence of all moments.

The case when $|\mathcal{P}| = 1$, say $\mathcal{P} = \{d\}$, $d \geq 2$, is exceptional. In this case, $a(n) = 1$ when n is a power of d , and $a(n) = 0$ otherwise. Then Y_N is uniformly distributed on the integers $\{0, \dots, \lfloor \log_d N \rfloor\}$, and thus $Y_N / \log N$ converges in distribution to a uniform distribution on $[0, 1/\log d]$, and therefore, Y_N is not asymptotically normal; further, the moment asymptotics differ from those in the theorem.

Ordered factorization problems in connection with that studied in this paper have a long history, tracing back to at least MacMahon's work (see [19]) in the early 1890's; later they were in most publications referred to as Kalmár's problem of "factorisatio numerorum" (see [15, 13]). Diverse properties of such factorizations have then been widely investigated, often in quite different contexts, one reason being that ordered factorizations are naturally encountered in many enumeration problems. For example, when $\mathcal{P} = \{2, 3, \dots\}$, $A(N) + 1$ equals the permanent of the Redheffer matrix; see [23]; also they appeared as the lower bound of certain biological problems; see [21]. See also [5, 17] for more information and references.

The first paper dealing with general ordered factorizations beyond the subset $\mathcal{P} = \{2, 3, \dots\}$ similar to our setting was Erdős [6], extending previous results by Hille [12]; see also [16]. Asymptotic normality of the special case of Theorem 1 when $\mathcal{P} = \{2, 3, \dots\}$ was treated in [14]. In this case, $\rho \approx 1.7286$ being the unique root > 1 that solves $\zeta(s) = 2$, where ζ denotes Riemann's zeta function. The proof given there relies on the determination of a zero-free region of the function $1 - z(\zeta(s) - 1)$, which in turn involves deep estimates from trigonometric sums (see also [18]). Such refined estimates are for general \mathcal{P} hard to establish. We replace this estimate by applying purely Tauberian arguments of Delange (see [4]), which require only analytic information of the involved Dirichlet series on its half-plane of convergence.

We will use Dirichlet series and the method of moments and derive asymptotic estimates for central moments of integral orders, which, by Frechet-Shohat's moment convergence theorem, will suffice to prove the theorem.

Proposition 1. For $k \geq 0$

$$\lim_{N \rightarrow \infty} \mathbb{E} \left(\frac{Y_N - \mu \log N}{\sigma \sqrt{\log N}} \right)^k = \begin{cases} \frac{k!}{(k/2)! 2^{k/2}}, & \text{if } k \text{ is even} \\ 0, & \text{if } k \text{ is odd,} \end{cases} \quad (1)$$

A straightforward application of the Tauberian theorem does not provide precise asymptotics for central moments beyond the first due to cancellation of major dominant terms and due to the fact that no error term is generally available via application of Tauberian arguments. The new idea we introduce in this paper is to take into account the feature that the mean is logarithmic and to shift-the-mean on the associated Dirichlet series, which nicely incorporates the cancellations of higher central moments in a surprisingly neat way.

It thus avoids completely the messy calculations and cancellations that the usual method of moments faces when dealing with higher central moments. A similar idea was previously applied to characterize the phase change of random m -ary search trees, where a nonlinear differential equation with an additive nature was encountered; see [3]. However, the tools used there are complex-analytic, in contrast to the purely Tauberian ones used here.

In the special case when $\mathcal{P} = \{2, 3, \dots\}$, our result may be interpreted as saying that the property of the zero-free region for the Dirichlet series $1 - z(\zeta(s) - 1)$ lies much deeper than the asymptotic normality of the random variables Y_N .

In addition to the number-theoretic interest *per se* of our results, we believe that the approach we use here also offers important methodological value for the study of similar problems. In particular, not only is the use of the method of moments very simple, but no analytic properties of the Dirichlet series beyond the abscissa of convergence are needed, which largely simplifies the analysis in many situations. For example, our approach can be readily applied to other factorizations such as branching or cyclic factorizations with algebraic or logarithmic singularities (see [13]). It can also be extended, coupling with suitable Tauberian theorems, to deal with ordered factorizations in additive arithmetic semigroups (see [16]) and components counts in ordered combinatorial structures (see [8]). Another possible extension is to the analysis of Euclidean algorithms; see [1, 10, 22].

In the periodic case when $\mathcal{P} \subseteq \{d^k : k \geq 1\}$ for some $d \geq 2$, $\mathcal{P}(s)$ has period $2\pi i / \log d$ and the usual Tauberian theorem does not apply. Instead we write $\mathcal{P}(s) = \tilde{\mathcal{P}}(d^{-s})$, where $\tilde{\mathcal{P}}(z) := \sum_{d^k \in \mathcal{P}} z^k$, and transform the multiplicative nature of the problem into an additive one on random compositions by taking logarithms. We replace the Tauberian theorem by the singularity analysis of Flajolet and Odlyzko (see [7] or [9, Chapter VI]) in the proof; the details are similar to the proof below, but simpler, so we omit them. In the rest of the paper we thus assume, for every $d \geq 2$,

$$\mathcal{P} \not\subseteq \{d^k\}_{k \geq 1}. \quad (2)$$

2 Dirichlet series, Delange's Tauberian theorem, and proofs

Generating functions. Let $a_m(n)$ denote the number of ordered factorizations of n into exactly m factors. Then

$$\mathcal{P}(s)^m = \sum_{n \geq 1} a_m(n) n^{-s},$$

in formal power series sense; analytically, we can take s satisfying $\mathcal{P}(\Re(s)) < \infty$. Thus if $e^{\Re(z)} \mathcal{P}(\Re(s)) < 1$, then by absolute convergence

$$\sum_{n \geq 1} n^{-s} \sum_{m \geq 0} a_m(n) e^{mz} = \sum_{m \geq 0} e^{mz} \mathcal{P}(s)^m = \frac{1}{1 - e^z \mathcal{P}(s)}. \quad (3)$$

Delange's Tauberian theorem. We need the following form of Delange's Tauberian theorem (see [4] or [20, Ch. III, Sec. 3]).

Let $F(s) := \sum_{n \geq 1} \alpha(n) n^{-s}$ be a Dirichlet series with nonnegative coefficients and convergent for $\Re(s) > \varrho > 0$. Assume (i) $F(s)$ is analytic for all points on $\Re(s) = \varrho$ except at $s = \varrho$; (ii)

for $s \sim \varrho$, $\Re(s) > \varrho$,

$$F(s) = \frac{G(s)}{(s - \varrho)^\beta} + H(s) \quad (\beta > 0),$$

where G and H are analytic at $s = \varrho$ with $G(\varrho) \neq 0$. Then

$$\sum_{n \leq N} \alpha(n) \sim \frac{G(\varrho)}{\varrho \Gamma(\beta)} N^\varrho (\log N)^{\beta-1}. \quad (4)$$

Asymptotics of $A(N)$. Taking $z = 0$ in (3), we obtain the Dirichlet series for $a(n) = \sum_{m \geq 0} a_m(n)$

$$\mathcal{A}(s) = \sum_{n \geq 1} a_n n^{-s} = \frac{1}{1 - \mathcal{P}(s)},$$

as long as $\Re(s) > \rho$. Note that the non-periodicity assumption (2) implies that $\mathcal{P}(s) \neq 1$ for all s with $\Re(s) = \rho$ but $s \neq \rho$. Hence $\mathcal{A}(s)$ is not only analytic in the open half-plane $\{s : \Re(s) > \rho\}$ but also on the boundary $\{s : \Re(s) = \rho\}$ except at $s = \rho$. The same holds true for all Dirichlet series we consider below.

Now for our $\mathcal{P}(s)$, since $\mathcal{P}'(\rho) = -\sum_{n \in \mathcal{P}} n^{-\rho} \log n < 0$, we see that $\mathcal{P}(s)$ has a simple zero at $s = \rho$, and thus $\mathcal{A}(s)$ has a simple pole at ρ with

$$\mathcal{A}(s) = \frac{1}{1 - \mathcal{P}(s)} \sim \frac{-1}{\mathcal{P}'(\rho)(s - \rho)},$$

as $s \rightarrow \rho$. Hence Delange's Tauberian theorem applies and we obtain

$$A(N) = \sum_{n \leq N} a(n) \sim RN^\rho, \quad R := -\frac{1}{\rho \mathcal{P}'(\rho)} = \frac{\mu}{\rho}. \quad (5)$$

Furthermore, we also have

$$\sum_{n \leq N} a(n)(\log n)^k \sim \frac{\mu}{\rho} N^\rho (\log N)^k \sim A(N)(\log N)^k,$$

either by repeating the same procedure for the Dirichlet series

$$(-1)^k \mathcal{A}^{(k)}(s) = \sum_{n \geq 1} a(n)(\log n)^k n^{-s} = (-1)^k \frac{d^k}{ds^k} \frac{1}{1 - \mathcal{P}(s)}, \quad (6)$$

or by using directly (5). The estimate will be used later.

The expected value of Y_N . By taking the derivative with respect to z on both sides of (3), we obtain

$$\sum_{n \geq 1} n^{-s} \sum_{m \geq 0} m a_m(n) = \frac{\mathcal{P}(s)}{(1 - \mathcal{P}(s))^2}.$$

Delange's Tauberian conditions being easily checked as above, we then obtain

$$\mathbb{E}(Y_N) = \frac{1}{A(N)} \sum_{n \leq N} \sum_{m \geq 0} m a_m(n) \sim \mu \log N.$$

Shifting-the-mean at the Dirichlet series level. For higher central moments, the idea we will use can *formally* be described by using Perron's integral representation as follows (using (3) and for simplicity assuming temporarily that N is not an integer).

$$\begin{aligned}\mathbb{E} \left(e^{(Y_N - \mu \log N)z} \right) &= \frac{1}{2\pi i A(N)} \int_{c-i\infty}^{c+i\infty} \frac{N^{s-\mu z}}{s} \frac{1}{1 - e^z \mathcal{P}(s)} ds \\ &= \frac{1}{2\pi i A(N)} \int_{c-i\infty}^{c+i\infty} \frac{N^s}{s} \frac{1}{(1 + \mu z/s)(1 - e^z \mathcal{P}(s + \mu z))} ds,\end{aligned}$$

where c is suitably chosen; the fact that the mean being of order $\log N$ is crucial here. We then *formally* expect that

$$\mathbb{E} (Y_N - \mu \log N)^k = \frac{k!}{2\pi i A(N)} \int_{c-i\infty}^{c+i\infty} \frac{N^s}{s} \mathcal{Q}_k(s) ds, \quad (7)$$

where $\mathcal{Q}_k(s)$ is the coefficient of z^k in the Taylor expansion (in z) of

$$\frac{1}{(1 + \mu z/s)(1 - e^z \mathcal{P}(s + \mu z))}.$$

While all steps can be easily justified (as done below), we cannot directly apply Delange's Tauberian theorem to $\mathcal{Q}_k(s)$ here since each \mathcal{Q}_k (except $\mathcal{Q}_0(s)$) is not a proper Dirichlet series, but involves additional powers of s^{-1} . This can be resolved as follows.

Shifting-the-mean at the coefficients level. We look at the "translation" of the preceding parameter-shift at the coefficient level. By definition

$$\begin{aligned}A(N) \mathbb{E} \left(e^{(Y_N - \mu \log N)z} \right) &= \sum_{n \leq N} \sum_{m \geq 0} a_m(n) e^{(m - \mu \log N)z} \\ &= \sum_{n \leq N} \sum_{m \geq 0} a_m(n) e^{(m - \mu \log n)z - \mu z \log(N/n)}.\end{aligned}$$

Let

$$b_k(n) := \sum_{m \geq 0} a_m(n) (m - \mu \log n)^k.$$

Then, by taking the coefficients of z^k on both sides, we obtain

$$A(N) \mathbb{E} (Y_N - \mu \log N)^k = \sum_{0 \leq \ell \leq k} \binom{k}{\ell} (-\mu)^{k-\ell} \sum_{n \leq N} b_\ell(n) \left(\log \frac{N}{n} \right)^{k-\ell}. \quad (8)$$

We will see that the growth order of $\sum_{n \leq N} b_k(n)$ is the power N^ρ times an additional logarithmic term; it then follows that the weighted sum on the right-hand side is of the same order by a simple partial summation (see below for more details).

Now observe that (assuming again that N is not an integer)

$$\frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} \frac{N^s}{s^m} \sum_{j \geq 1} \alpha(j) j^{-s} ds = \frac{1}{(m-1)!} \sum_{n \leq N} \alpha(n) \left(\log \frac{N}{n} \right)^{m-1} \quad (m = 1, 2, \dots),$$

where c is taken to be any real number greater than the abscissa of absolute convergence of the function defined by the series $\sum_{j \geq 1} \alpha(j) j^{-s}$. So, this, together with (8), justifies (7).

A probabilistic interpretation. Given N , consider a random factorization of a number $n \leq N$, namely, a random product $p_1 \cdots p_m \leq n$ with all $p_j \in \mathcal{P}$ (uniformly distributed over all $A(N)$ possible factorizations). Let Y_N be the number of factors ($= m$) and ν_N be their product ($= n$). Then

$$A(N)\mathbb{E}(Y_N - \mu \log \nu_N)^k = \sum_{n \leq N} b_k(n),$$

which gives a probabilistic interpretation of the partial sum.

The Dirichlet series of $b_k(n)$. Define the Dirichlet series

$$\mathcal{M}_k(s) := \sum_{n \geq 1} b_k(n) n^{-s} = \sum_{n \geq 1} n^{-s} \sum_{m \geq 0} a_n(m) (m - \mu \log n)^k. \quad (9)$$

Note that $a_m(n) > 0$ implies that $m \leq \log_2 n$, so that

$$(m - \mu \log n)^k = O((\log n)^k),$$

for all non-zero terms. Hence $\mathcal{M}_k(s)$ is absolutely convergent when $\Re(s) > \rho$ because $\mathcal{A}(s) = 1/(1 - \mathcal{P}(s))$ is. Now if $\Re(s) > \rho$ and $|z|$ is sufficiently small, then, by (3),

$$\sum_{k \geq 0} \frac{\mathcal{M}_k(s)}{k!} z^k = \sum_{n \geq 1} n^{-s} \sum_m a_n(m) e^{(m - \mu \log n)z} = \frac{1}{1 - e^z \mathcal{P}(s + \mu z)}. \quad (10)$$

With these $\mathcal{M}_k(s)$, the generating function $\mathcal{Q}_k(s)$ can be decomposed as

$$\mathcal{Q}_k(s) = \sum_{0 \leq \ell \leq k} \left(\frac{-\mu}{s} \right)^{k-\ell} \frac{\mathcal{M}_\ell(s)}{\ell!}. \quad (11)$$

Our strategy will then to apply Delange's Tauberian theorem to \mathcal{M}_k for even k and some auxiliary Dirichlet series for odd k , and then the asymptotics of the k -th central moment can be obtained easily since terms with index $\ell < k$ in (11) will be asymptotically negligible. Indeed, we will use (8).

Recurrence of $\mathcal{M}_k(s)$. We now focus on properties of $\mathcal{M}_k(s)$. By writing (10) in the form

$$(1 - e^z \mathcal{P}(s + \mu z)) \sum_{\ell \geq 0} \frac{\mathcal{M}_\ell(s)}{\ell!} z^\ell = 1,$$

we see that $\mathcal{M}_k(s)$ satisfies the recurrence

$$\mathcal{M}_k(s) = \frac{1}{1 - \mathcal{P}(s)} \sum_{0 \leq j < k} \binom{k}{j} \mathcal{M}_j(s) \mathcal{B}_{k-j}(s) \quad (k \geq 1), \quad (12)$$

with $\mathcal{M}_0(s) = 1/(1 - \mathcal{P}(s))$, where

$$\mathcal{B}_k(s) := \sum_{0 \leq \ell \leq k} \binom{k}{\ell} \mu^\ell \mathcal{P}^{(\ell)}(s).$$

For example, $\mathcal{M}_1(s) = \mathcal{B}_1(s)/(1 - \mathcal{P}(s))^2 = (\mathcal{P}(s) + \mu\mathcal{P}'(s))/(1 - \mathcal{P}(s))^2$.

Note that each $\mathcal{B}_k(s)$ is analytic for $\Re(s) > \kappa$ and, in particular, for $\Re(s) \geq \rho$. Moreover, the crucial property here is

$$\mathcal{B}_1(\rho) = \mathcal{P}(\rho) + \mu\mathcal{P}'(\rho) = 1 - 1 = 0,$$

by our construction. Similarly,

$$\mathcal{B}_2(\rho) = \mathcal{P}(\rho) + 2\mu\mathcal{P}'(\rho) + \mu^2\mathcal{P}''(\rho) = \mu^2\mathcal{P}''(\rho) - 1 = \sigma^2/\mu,$$

and $\mathcal{B}_1'(\rho) = \sigma^2/\mu^2$.

On the other hand, by (12), we see that $\mathcal{M}_k(s)$ is analytic for $\Re(s) > \rho$ and for $\Re(s) = \rho$ except at $s = \rho$. Furthermore, because $\mathcal{B}_1(\rho) = 0$, it follows by induction from (12), that at $s = \rho$, $\mathcal{M}_k(s)$ has a pole of order at most $\lfloor k/2 \rfloor + 1$.

Even moments. More precisely, for even $k = 2\ell$, we get by induction

$$\mathcal{M}_k(s) \sim c_k(s - \rho)^{-k/2-1},$$

where

$$c_k = \binom{k}{2} \mu \mathcal{B}_2(\rho) c_{k-2} = \frac{k(k-1)}{2} \sigma^2 c_{k-2},$$

with $c_0 = \mu$, which is solved to be

$$c_k = \mu \left(\frac{\sigma^2}{2} \right)^{k/2} k!.$$

We now apply Delange's Tauberian theorem and obtain

$$\begin{aligned} \mathbb{E}(Y_N - \mu \log \nu_N)^k &= \frac{1}{A(N)} \sum_{n \leq N} b_k(n) \\ &\sim \frac{c_k}{\rho \Gamma(k/2 + 1) A(N)} N^\rho (\log N)^{k/2} \\ &\sim \frac{k!}{2^{k/2} (k/2)!} \sigma^k (\log N)^{k/2}. \end{aligned} \tag{13}$$

Odd moments. Let now $k = 2\ell - 1$, $\ell \geq 1$. Since the coefficients $b_k(n)$ are not necessarily nonnegative, we cannot directly apply Delange's Tauberian theorem. Instead, we consider the following two auxiliary Dirichlet series

$$D_1(s) := \sum_{n \geq 1} n^{-s} \sum_{m \geq 0} a_m(n) ((m - \mu \log n)^k + (\log n)^{k/2})^2,$$

and, see (9) and (6),

$$\begin{aligned} D_2(s) &:= \sum_{n \geq 1} n^{-s} \sum_{m \geq 0} a_m(n) ((m - \mu \log n)^{2k} + (\log n)^k) \\ &= \mathcal{M}_{2k}(s) + (-1)^k \mathcal{A}^{(k)}(s). \end{aligned}$$

The two Dirichlet series have only nonnegative coefficients, and we will show that Delange's Tauberian theorem can be applied to both series. The leading terms will cancel and we will have

$$\frac{1}{A(N)} \sum_{n \leq N} b_k(n) (\log n)^{k/2} = o((\log N)^k). \quad (14)$$

From this, we use the monotonicity of $(\log n)^{k/2}$ and elementary arguments to recover the desired estimate

$$\mathbb{E}(Y_N - \mu \log \nu_N)^k = \frac{1}{A(N)} \sum_{n \leq N} b_k(n) = o((\log N)^{k/2}). \quad (15)$$

Proof of (14). Let

$$D_3(s) := \sum_{n \geq 1} (\log n)^{k/2} b_k(n) n^{-s}.$$

Then $D_1(s) = D_2(s) + 2D_3(s)$. By the discussions above, we can apply Delange's theorem to $D_2(s)$ and obtain

$$\frac{1}{A(N)} \sum_{n \leq N} \sum_{m \geq 0} a_m(n) ((m - \mu \log n)^{2k} + (\log n)^k) \sim C_k (\log N)^k, \quad (16)$$

where $C_k = (2k)! \sigma^{2k} / (2^k k!) + 1$ (this value is however immaterial).

We now show that the partial sum of the coefficients of $D_1(s)$ has asymptotically the same dominant term. We start from the representation ($k = 2\ell - 1$)

$$D_3(s) = (-1)^\ell \pi^{-1/2} \int_0^\infty \mathcal{M}_k^{(\ell)}(s+t) t^{-1/2} dt,$$

for $\Re s > \rho$, because $(-1)^\ell \mathcal{M}_k^{(\ell)}(s) = \sum_{n \geq 1} b_k(n) (\log n)^\ell n^{-s}$ and

$$\begin{aligned} (-1)^\ell \int_0^\infty \mathcal{M}_k^{(\ell)}(s+t) t^{-1/2} dt &= \sum_{n \geq 1} b_k(n) (\log n)^\ell n^{-s} \int_0^\infty e^{-t \log n} t^{-1/2} dt \\ &= \Gamma(\tfrac{1}{2}) \sum_{n \geq 1} b_k(n) (\log n)^{k/2} n^{-s} \\ &= \sqrt{\pi} D_3(s). \end{aligned}$$

We now consider the local behavior of $D_3(s)$ when $s \sim \rho$. First, $\mathcal{M}_k(s)$ has a pole at $s = \rho$ with leading term $c'_k (s - \rho)^{-(k+1)/2}$, for some c'_k . Thus $\mathcal{M}_k^{(\ell)}(s)$ has a pole with local behavior $c''_k (s - \rho)^{-k-1}$. It follows

that for small $|w|$ and $\Re(w) > 0$,

$$\begin{aligned}
D_3(\rho + w) &= (-1)^\ell \pi^{-1/2} \int_0^\infty \mathcal{M}_k^{(\ell)}(\rho + w + t) t^{-1/2} dt \\
&= O\left(\int_0^\infty |w + t|^{-k-1} t^{-1/2} dt\right) \\
&= O\left(\int_0^{|w|} |w|^{-k-1} t^{-1/2} dt + \int_{|w|}^\infty t^{-k-3/2} dt\right) \\
&= O(|w|^{-k-1/2}) \\
&= o(|w|^{-k-1}).
\end{aligned}$$

Since $D_1(s) = D_2(s) + D_3(s)$ has all coefficients nonnegative, we can now apply Delange's theorem to $D_1(s)$ and conclude that

$$\frac{1}{A(N)} \sum_{n \leq N} \sum_{m \geq 0} a_m(n) \left((m - \mu \log n)^k + (\log n)^{k/2} \right)^2 \sim C_k (\log N)^k.$$

This, together with (16), proves (14).

Proof of (15). Let

$$B_k(x) := \sum_{n \leq x} b_k(n) (\log n)^{k/2},$$

and for $x \geq 2$, $\varphi(x) := (\log x)^{-k/2}$. Then

$$\begin{aligned}
\int_2^N B_k(x) \varphi'(x) dx &= \sum_{2 \leq n \leq N} b_k(n) (\log n)^{k/2} \int_n^N \varphi'(x) dx \\
&= \sum_{2 \leq n \leq N} b_k(n) (\log n)^{k/2} \left((\log N)^{-k/2} - (\log n)^{-k/2} \right) \\
&= B_k(N) (\log N)^{-k/2} - \sum_{2 \leq n \leq N} b_k(n).
\end{aligned}$$

Thus, by (14),

$$\begin{aligned}
\sum_{1 \leq n \leq N} b_k(n) &= b_k(1) + B_k(N) (\log N)^{-k/2} - \int_2^N B_k(x) \varphi'(x) dx \\
&= O(1) + o(N^\rho (\log N)^{k/2}) + \frac{k}{2} \int_2^N B_k(x) x^{-1} (\log x)^{-k/2-1} dx \\
&= O(1) + o(N^\rho (\log N)^{k/2}) + o\left(\int_2^N x^{\rho-1} (\log x)^{k/2-1} dx\right) \\
&= o(N^\rho (\log N)^{k/2}),
\end{aligned}$$

as required.

From $Y_N - \mu \log \nu_N$ **to** $Y_N - \mu \log N$. The two estimates (13) and (15) imply

$$\mathbb{E} \left(\frac{Y_N - \mu \log \nu_N}{\sigma \sqrt{\log N}} \right)^k \rightarrow \begin{cases} \frac{k!}{(k/2)! 2^{k/2}}, & \text{if } k \text{ is even} \\ 0, & \text{if } k \text{ is odd,} \end{cases} \quad (17)$$

which in turn implies, by the method of moments, that

$$\frac{Y_N - \mu \log \nu_N}{\sigma \sqrt{\log N}} \xrightarrow{d} \mathcal{N}(0, 1).$$

Our final task is to prove the same asymptotics (1) from the two estimates (13) and (15). To that purpose, define $S_k(x) = 0$ if $x < 2$ and

$$S_k(x) := \sum_{n \leq x} b_k(n) \quad (x \geq 2).$$

We use (8) and the cruder estimates (by (13), (15) and (5))

$$S_\ell(x) = O(A(x)(\log x)^{\ell/2}) = O(x^\rho (\log x)^{\ell/2}),$$

for $\ell = 0, \dots, k-1$. With this, we have

$$\begin{aligned} & \sum_{0 \leq \ell < k} \binom{k}{\ell} (-\mu)^{k-\ell} \sum_{n \leq N} b_\ell(n) \left(\log \frac{N}{n} \right)^{k-\ell} \\ &= O \left((\log N)^k + \sum_{0 \leq \ell < k} \binom{k}{\ell} \mu^{k-\ell} \int_2^N \left(\log \frac{N}{x} \right)^{k-\ell} dS_\ell(x) \right). \end{aligned}$$

Now for each $\ell = 0, \dots, k-1$,

$$\begin{aligned} \int_2^N \left(\log \frac{N}{x} \right)^{k-\ell} dS_\ell(x) &= O \left(\int_2^N \left(\log \frac{N}{x} \right)^{k-\ell-1} x^{-1} S_\ell(x) dx \right) \\ &= O \left(\int_2^N \left(\log \frac{N}{x} \right)^{k-\ell-1} x^{\rho-1} (\log x)^{\ell/2} dx \right). \end{aligned}$$

Splitting the integral at $x = N/2$, and making the change of variables $x \mapsto N/x$ for the first half, we see that

$$\begin{aligned} & \int_2^N \left(\log \frac{N}{x} \right)^{k-\ell-1} x^{\rho-1} (\log x)^{\ell/2} dx \\ &= O \left(N^\rho \int_2^{N/2} x^{-\rho-1} (\log x)^{k-1-\ell} \left(\log \frac{N}{x} \right)^{\ell/2} dx + \int_{N/2}^N x^{\rho-1} (\log x)^{\ell/2} dx \right) \\ &= O(N^\rho (\log N)^{\ell/2}) \\ &= o(N^\rho (\log N)^{k/2}), \end{aligned}$$

for $0 \leq \ell \leq k-1$. This proves that

$$\mathbb{E}(Y_N - \mu \log N)^k = \frac{1}{A(N)} \sum_{n \leq N} b_k(n) + o((\log N)^{k/2}),$$

and thus the estimates in (1) hold by (13) and (15).

An alternative argument. To bridge (17) and (1), we can also argue as follows. Consider the sum

$$\mathbb{E} (\log N - \log \nu_N)^k = \frac{1}{A(N)} \sum_{n \leq N} a(n) \left(\log \frac{N}{n} \right)^k,$$

which is $O(1)$ by a similar summation by parts argument as used above. Then for even k

$$\|\log N - \log \nu_N\|_k = O(1).$$

By Hölder's inequality, this holds true also for every $k \geq 0$. Consequently, using again Hölder's inequality, we deduce (1).

3 Conclusions and additional remarks

While a direct application of Tauberian theorems leads to results of the form

$$\mathbb{E}(Y_N) \sim \mu \log N,$$

we indeed prove, still relying on Tauberian arguments, that

$$\mathbb{E}(Y_N) = \mu \log N + o(\sqrt{\log N}),$$

(a special case of Proposition 1). This shows the power of our approach. However, the estimates (1) we derived are not strong enough so as to prove more effective bounds such as the convergence rate to normality (or the Berry-Esseen bound).

Another corollary to our moment convergence result is the following asymptotic approximations to all absolute central moments

$$\mathbb{E}|Y_N - \mu \log N|^\beta \sim 2^{\beta/2} \pi^{-1/2} \Gamma\left(\frac{\beta+1}{2}\right) (\log N)^{\beta/2},$$

for all $\beta \geq 0$, which seem difficult to get directly from Dirichlet series.

On the other hand, when $z \in (-\log \mathcal{P}(\kappa), \infty)$, one can apply directly Delange's Tauberian theorem to the generating function

$$\frac{1}{1 - e^z P(s)},$$

(instead of to the Dirichlet series of higher moments obtained above by Taylor expansions in z); this results in the asymptotic approximation

$$\mathbb{E} (e^{zY_N}) \sim \frac{\rho P'(\rho)}{\rho(z) e^z P'(\rho(z))} N^{\rho(z)-\rho},$$

where $\rho(z)$ solves the equation $1 = e^z P(\rho(z))$ with $\rho(0) = \rho$. From this approximation, one might expect asymptotic normality by straightforward argument. However, the asymptotic result so obtained holds only pointwise, and the uniformity in z is missing here. While the gap of uniformity may perhaps be filled

by applying suitable Tauberian theorems with remainders, the use of Delange's Tauberian theorems is computationally simpler and technically less involved.

It is clear from our proof that Theorem 1 actually holds for any Dirichlet series $\mathcal{P}(s)$ with nonnegative coefficients and satisfying the conditions of Theorem 1. Thus the restriction of \mathcal{P} to a subset of positive integers is not essential. For example, one can consider the *ordered totient factorizations* with $\mathcal{P}(s) = \sum_{n \geq 3} \phi(n)^{-s}$, where $\phi(n)$ is Euler's totient function, namely, the number of positive integers $\leq n$ and relatively prime to n . In this case, $\kappa = 1$ and $\rho \approx 2.26386$ since

$$\sum_{n \geq 1} \phi(n)^{-s} = \zeta(s) \prod_{p: \text{prime}} (1 - p^{-s} + (p-1)^{-s});$$

see [2] for a detailed studied of this Dirichlet series.

How to compute ρ to high degree of precision? In general, the problem is not easy, for example, if $\mathcal{P}(s) = \sum_{n \geq 2} [n^\beta (\log n)^c]^{-s}$ for $\beta, c > 0$; the case of totient factorization is similar. The easy cases are when $\mathcal{P}(s)$ can be expressed in terms of ζ -functions such as $\mathcal{P}(s) = \zeta(s) - 1$ (all integers > 1) or $\mathcal{P}(s) = \zeta(s)/\zeta(2s) - 1$ (square-free integers > 1). Take now $\mathcal{P}(s) = \sum_{p: \text{prime}} p^{-s}$. The zero of $\mathcal{P}(s) = 1$ can also be easily computed by using the relation (see [11])

$$\sum_{p: \text{prime}} p^{-s} = \sum_{k \geq 1} \frac{\mu(k)}{k} \log \zeta(ks) \quad (\Re(s) > 1),$$

where $\mu(k)$ is Möbius function. This readily gives

$$\rho \approx 1.39943\,33287\,26330\,31820\,28072\dots,$$

and

$$\begin{aligned} \mu &\approx 0.57764\,86251\,95138\,05440\,61351\dots, \\ \sigma^2 &\approx 0.48439\,65045\,13598\,28128\,07456\dots \end{aligned}$$

We indicated a few directions to which our approach can be extended in Introduction. But can a similar idea be modified so as to deal with arithmetic functions with mean other than $\log N$?

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